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A health impact assessment of changes in NDVI on all-cause mortality across 1041 global cities

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Abstract

Urban greenspaces are associated with improved health and climate resiliency. Large scale health impact assessments of urban greenspace and mortality have been limited to American and European cities. We estimated changes in mortality associated with observed differences in population-weighted greenest season normalized difference vegetation index (NDVI) between 2014–2018 and 2019–2023 across 1041 global cities representing 174 countries. We used publicly available high-resolution satellite-derived estimates of NDVI and population, baseline disease rates from the Global Burden of Disease study, and a hazard ratio of the association between NDVI and all-cause mortality from an epidemiological meta-analysis. We found that urban greenspace varies substantially across cities (NDVI mean: 0.270, range: 0.072, 0.580) and by climate classification and geographic region. Despite modest global average changes in NDVI from 2014–2018 to 2019–2023, NDVI has changed by over ±20% in individual cities. Median regional changes were largest in South-eastern Asia (−0.022), Sub-Saharan Africa (−0.010) and Eastern Asia (+0.014) and most stable in arid climates (<0.000). These changes were associated with a global mean of 0.19 (95% CI: 0.12, 0.27) additional annual deaths per 100 000 in the 2020 population, ranging from 24.44 fewer to 21.84 more deaths per 100 000 across cities. Health impact assessments of NDVI and all-cause mortality have largely been conducted in European and North American cities, where we found NDVI was generally higher and more stable. Our results highlight large heterogeneity in urban greenspace extent and variability across global cities and the importance of characterizing the relationship between health and NDVI in more diverse contexts.

1. Introduction

Over half of the world's population lives in cities and this share is predicted to grow to two-thirds by 2050 [1]. Urbanization has been accompanied by the pollution of natural resources, like air and water, and the destruction of natural environments. While cities are responsible for over 80% of global greenhouse gas emissions [2], emissions per capita in developed nations tend to be lower in cities than in less dense communities due to more efficient transportation, energy production, and land use [3]. In addition, cities can be effective entities of change and can provide a large enough scale to create meaningful change while remaining small enough to test policies that might not be feasible at a national scale. City-level interventions to increase urban nature offer a climate adaptation strategy with health advantages.

Urban greenspaces (such as city parks and tree-lined streets) and blue spaces (like lakes, rivers, and coastlines) have been linked to improvements in human health and climate resiliency. Greenspace has been associated with improved mental and physical health [4]. Systematic reviews support an association between increased residential greenspace and decreased risk of depression and anxiety [5], low birth weight [6], cardiovascular events [7], lung and prostate cancer mortality [8], and all-cause mortality [9]. While less studied, blue space has also been linked to improved health [10]. Urban green and blue spaces have also been associated with beneficial environmental outcomes such as better storm water management and heat regulation, increased biodiversity, and reductions in air pollution and ultraviolet radiation [11–14]. Greenspace has generally been the focus of urban nature policies and interventions, as it is more feasible to create than blue space. Three main pathways have been hypothesized to link greenspace with health: reduced environmental harm (i.e. less heat, noise, and air pollution), restoration capacities (i.e. reduced stress), and building capacities (i.e. increased physical activity and social gathering) [15]. Mediation studies have found evidence that greenspace is associated with health through better air quality, increased physical activity, and reduced stress [16].

Studies linking greenspace to reductions in mortality have generally used the normalized difference vegetation index (NDVI). NDVI is a satellite-derived measure that uses red and near-infrared light waves to determine the health and density of vegetation [17]. Generally, negative values correspond to water, snow and ice, values near zero represent barren land and higher positive values indicate greener, denser vegetation. Two studies estimating the number of deaths associated with hypothetical changes in NDVI in European and American cities indicated that increasing urban greenspace can substantially reduce mortality. A 2021 study of 978 cities in 31 European countries found that if cities were to increase their NDVI to a level equivalent with the World Health Organization's recommendation of universal access to greenspace, 42 968 natural deaths could be avoided annually (95% confidence interval (CI): 32 296, 64 177) among adults [18]. A 2022 study of the 35 most populous American cities found that if overall NDVI was increased by 0.1, 38 000 deaths (95% CI: 28 640–57 281) could have been avoided in 2019 among those aged 65 years and older [19]. These studies suggest that urban greenspace can reduce premature mortality. However, a global health impact assessment is needed to characterize the potential health benefits from increasing greenspace across a broader range of climate and regional contexts.

In 2020, The Lancet Countdown began tracking urban greenspace across a global set of cities. The Lancet Countdown is an annual publication dedicated to tracking progress towards the goals of the Paris Agreement and documenting the health implications of climate change [20]. We updated the Lancet Countdown methodology to capture population at a finer scale (100 m instead of 1 km resolution) and to remove surface water from the urban greenspace calculation. We further conducted a health impact assessment of the increases or reductions in deaths associated with changes in urban greenspace over time across the 1041 global cities included in the Lancet Countdown's greenspace analysis. We characterized urban greenspace across these cities from 2014 to 2023 and estimated the changes in mortality associated with differences in greenspace between two 5 year periods, 2014–2018 and 2019–2023. We chose 5 year time periods to minimize the effect of year-to-year extremes and capture longer-term trends in urban greenspace exposure. The results of this study can be used to compare greenspace changes over time and the associated health implications across cities globally.

2. Methods

We estimated peak seasonal urban greenspace using population-weighted NDVI from 2014 to 2023, in 1041 cities across 174 countries. We then estimated the mortality change in each city associated with the difference in NDVI between two 5 year periods, from 2014–2018–2019–2023. We defined urban extents using the Global Human Settlement Urban Centre Database (GHS-UCDB), which provides a consistent methodology based on population and remote sensing data [21]. We included the 1041 cities for which urban greenspace was estimated by the Lancet Countdown on health and climate change. The Lancet Countdown included cities if they were the most populous in their country or had over 500 000 inhabitants. Twenty-two small, mainly island, countries did not have cities in the GHS-UCDB and were not represented in the analysis (see Supplemental Data List S1, for a complete list).

2.1. Population-weighted greenest season NDVI

For NDVI, we used Landsat 8 satellite imagery, accessed through Google Earth Engine (GEE) [22]. Landsat data are available at the 30 m resolution with new images captured approximately every 16 days for a given location. Following the methods used by many of the studies included in the meta-analysis of greenspace and mortality that we use for our exposure response function, we removed pixels representing water and clouds. To remove cloudy pixels, we used the 'Landsat.simpleComposite' algorithm from GEE. We used the Joint Research Centre (JRC)'s Landsat-derived global surface water dataset (30 m resolution) to exclude pixels that were classified as 'permanent water [23].' We used the 2015 JRC dataset to mask water pixels in the 2014–2018 images and the 2020 dataset to mask water pixels in the 2019–2023 images. We then downscaled the NDVI dataset to the 100 m resolution to align with our population dataset.

We used Rojas-Rueda *et al* [9]'s meta-analysis to define the epidemiologic relationship between increased NDVI and reductions in all-cause mortality. The nine longitudinal studies included in this meta-analysis had follow-up periods ranging from four to 18 years and measured urban greenspace using NDVI. Three studies defined greenspace using the average NDVI value from the greenest season of each year within the study period, while four others uses the greenest day or greenest month from a representative year or years [24–32]. To align with the most commonly used exposure metric by the studies included in this meta-analysis, we therefore calculated the population-weighted greenest season NDVI. After removing water pixels, we calculated pixel-level NDVI averages for each season: December 1 of the previous year through February 28, March 1 through May 31, June 1 through August 31, and September 1 through November 30. We averaged all Landsat images within these time periods. We combined our pixel-level average seasonal NDVI estimates with gridded total population data from JRC's 100 m GHS Layer to calculate a population-weighted seasonal average NDVI for each city (equation (1)):

$$\frac{\sum_{i=1}^{n}\left(\mathrm{NDVI}_i * \mathrm{population}_i\right)}{\sum_{i=1}^{n}\left(\mathrm{population}_i\right)}. \tag{1}$$

This dataset is updated every five years. We used the 2015 population spatial distribution for years 2014–2018 and the 2020 population spatial distribution for years 2019–2023. For each year, we selected the highest population-weighted seasonal average NDVI, representing the greenest or peak season, for each city.

2.2. Health impact assessment

We used a linear health impact function to estimate the annual change in premature deaths (more or fewer) associated with changes in urban greenspace (decreases or increases) following previous health impact assessments of greenspace on mortality [33, 34]. The health impact equation is a function of baseline mortality rates, population, changes in greenspace exposure, and the exposure-response function between NDVI and all-cause mortality. We first calculated the population attributable fraction (PAF) of deaths related to insufficient green area (equation (2)). We used the difference between the average 2014–2018 and 2019–2023 population-weighted greenest season NDVI to define changes in urban greenspace at the 100 m pixel (i) level to align with the resolution of our population dataset ($\Delta\mathrm{NDVI}_i$). We opted to use a 5 year average rather than compare individual years, because we observed large inter-annual variability in NDVI. To calculate the PAF, we used the hazard ratio (HR) from a meta-analysis of the protective effect of NDVI on all-cause mortality, which found a pooled HR of 0.96 (95% CI: 0.94, 0.97) for each 0.1 increase in NDVI within 500 m of a person's home [9]. We scaled changes in NDVI by the unit increase of the hazard-ratio (0.1 increases in NDVI). We calculated this value for each 100 m pixel (i) (equation (2)):

$$\mathrm{PAF}_i = 1 - \frac{1}{\mathrm{HR}^{\frac{\Delta\mathrm{NDVI}_i}{0.1}}}. \tag{2}$$

We summed the product of 2020 country-level baseline mortality rates (y_0) from the Global Burden of Disease (GBD) 2021 study [35], 2020 gridded population estimates (pop_i) from JRC [36], and the PAF_i across each 100 m pixel (i) within the urban boundary to calculate the city change in annual greenspace related mortality (Δmortality) (equation (3)). While the Rojas-Rueda *et al* meta-analysis restricted to adults aged 18 and over, we used the total population because that was the gridded population data available from JRC at the 100 m pixel resolution. Though children were not included in the Rojas-Rueda *et al* study, systematic reviews have linked increased NDVI to higher birth weights [6] and increased physical activity among children and adolescents [37], and a large national study found that higher NDVI was associated with decreased risk of infant and under-5 mortality [38].

$$\Delta\mathrm{mortality} = \sum\left(y_0 * \mathrm{pop}_i * \mathrm{PAF}_i\right). \tag{3}$$

2.3. Quantifying uncertainty

We ran 10 000 Monte Carlo simulations of equation (3) for each city to estimate uncertainty intervals of our mortality estimates from changes in NDVI. We used estimates of error provided in the meta-analysis [9] and by the GBD study [35] to draw from normal distributions of the HR and baseline mortality estimates. For each simulation, the same draw of the HR was used for all cities.

2.4. Urban area groupings

We categorize cities by geographic region using the United Nations Statistical Division sub-regional definitions (figure S1) [39] and by climate region using the Köppen–Geiger Climate Classification System (figure S2) [40]. The sub-regional definitions break continental regions into smaller groups and are used by the United Nations in publications [39]. The Köppen–Geiger Climate Classification System divides the climate into five broad categories based on monthly precipitation and temperature and has been used to understand global vegetation patterns [40].

3. Results

Globally, the annual average population-weighted greenest season NDVI has remained relatively consistent over the past decade (figure 1). The lowest global average in this period was 0.276 (years 2018 and 2023) and the highest was 0.281 (years 2014 and 2015). The average range in annual NDVI over

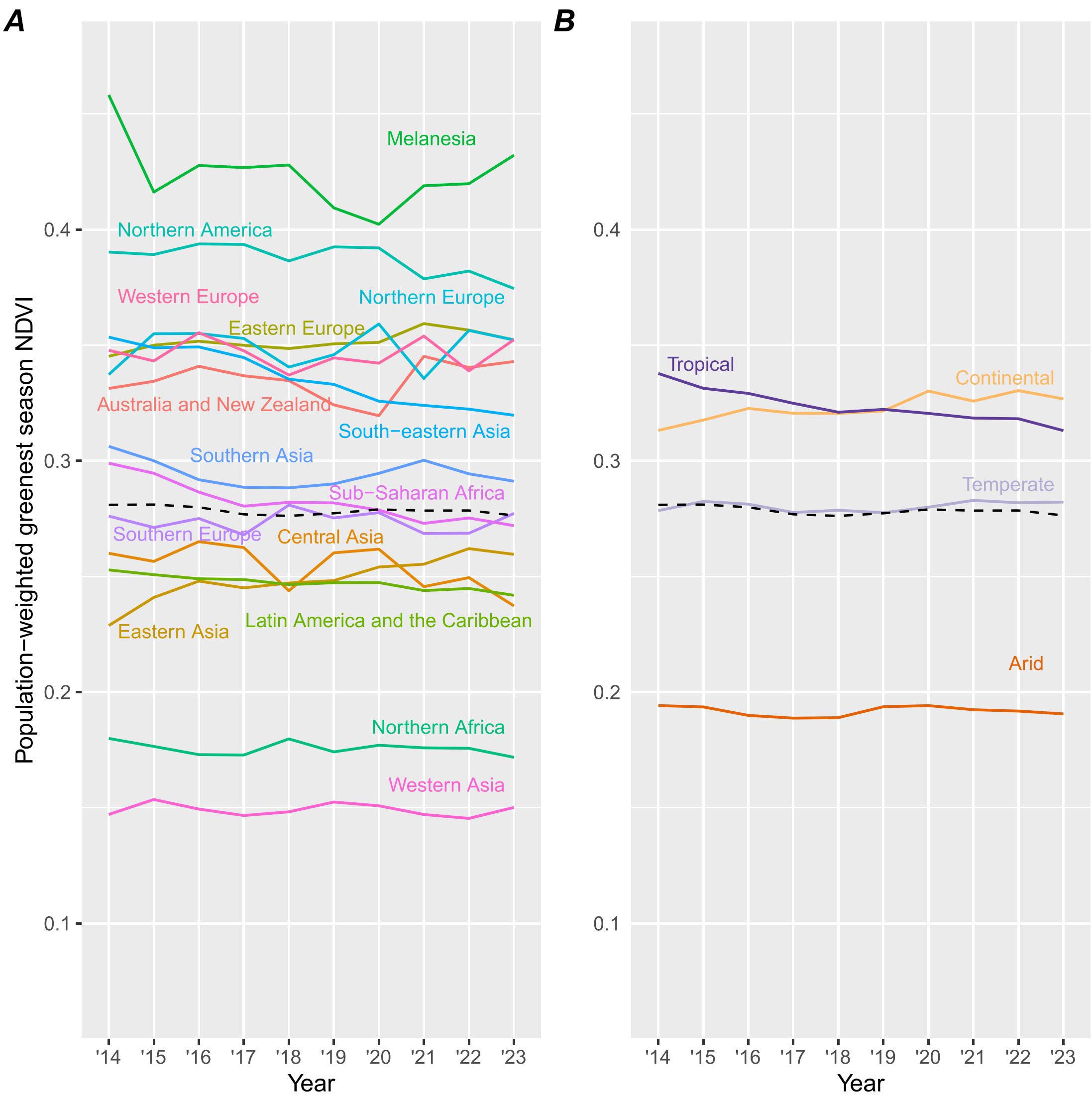

Figure 1. Population-weighted greenest season average normalized difference vegetation index (NDVI) from 2014–2023 by geographic region (panel (A)) and climate classification (panel (B)). The 1041-city average is shown with the black dashed line. The polar climate classification was removed from panel (B), because only one city from this climate zone is included in the analysis (El Alto, Bolivia).

the past decade across all cities was 0.056. Some cities' NDVI ranged less than 0.01 over the last ten years, while others experienced swings of over 0.2. Regionally, cities in Sub-Saharan Africa, Eastern Asia, and Southern Asia had larger inter-annual variation, with an average decadal range in NDVI of ∼0.07, while cities in Northern Africa and Central Asia generally show a flatter trend (range in 10 year annual NDVI: ∼0.03). NDVI has remained comparatively stable in arid cities, with an average city 10 year range of 0.037, about half that of cities in other climate zones. All climate classifications and roughly half the geographic regions had individual cities with changes in NDVI of over 0.1 from 2014–2023 (figure S3). Considering the percent change in annual average peak season NDVI (figure S4), the greenest year of the past decade was over 20% higher than the least green year in roughly half of all cities.

The average population-weighted peak season NDVI varies greatly across global cities (figure 2). In the most recent 5 year period, the global average greenest season NDVI was 0.270, ranging from 0.072 to 0.580 across cities. Peak season NDVI is correlated with geographic region (figure S5) and Köppen–Geiger climate classification (figure S6). Peak-season 2019–2023 NDVI was highest on average in Melanesia (0.417), North America (0.384), and most of Europe including Eastern (0.354), Northern (0.350), and Western (0.346) Europe. Western Asia and North Africa were the least green, with NDVI averages of 0.149 and 0.175 across their cities, respectively. In terms of climate classification, the average greenest season NDVI for 2019–2023 was 0.193 in arid, 0.281 in temperate, 0.319 in tropical, and 0.327 across continental cities.

Globally, the 5 year greenest season average NDVI decreased slightly from 0.279 in 2014–2018 to 0.270 in

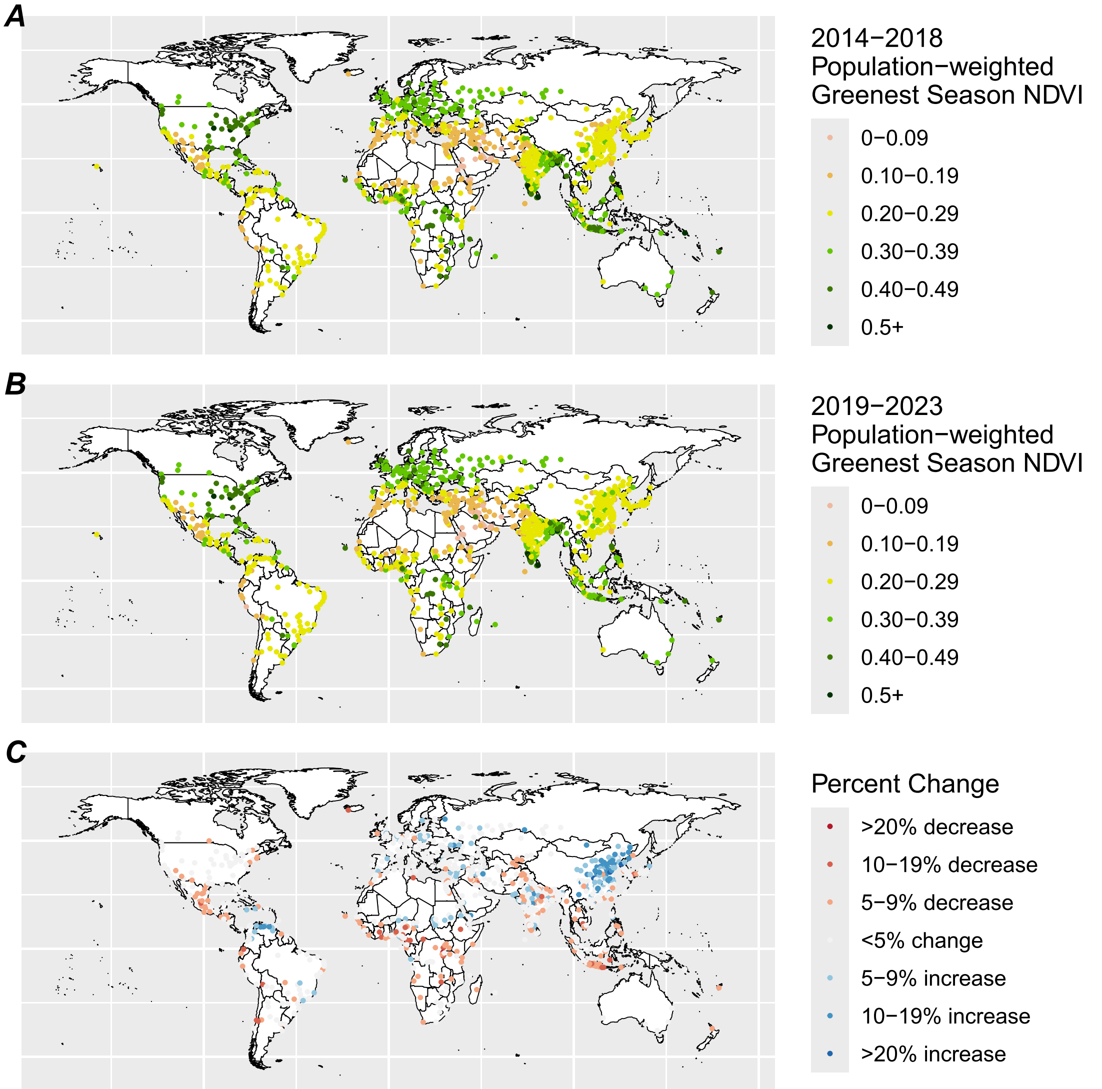

Figure 2. Average population-weighted greenest season normalized difference vegetation index (NDVI) for 2014–2018 (panel (A)) and 2019–2023 (panel (B)) and the percent change between the two time periods (panel (C)) for 1041 cities globally.

2019–2023, with an average city-level percent change of −0.46%. However, this relatively small global change masks large differences across individual cities. The percent change between these two periods ranged from −22.29% to 29.38% across the 1041 cities.

Regional NDVI averages across the two 5 year periods were relatively stable (figure 3(A)). The median regional NDVI changed by more than 0.01 in only four geographic regions: Melanesia (−0.018), South-eastern Asia (−0.022), Sub-Saharan Africa (−0.010) and Eastern Asia (+0.014). The regional range of absolute changes in NDVI ranged from 0.028 in Southern Europe to 0.095 in Eastern Asia. Every region had cities that became greener and others that became less green from 2014–2018 to 2019–2023.

There was a similarly large spread within each region and notable differences across regions in the percent change in NDVI between 2014–2018 and 2019–2023 (figure 3(B)). The median percent change was greater than 5% in South-eastern Asia (−6.3%) and Eastern Asia (+6.2%). Sub-Saharan Africa had 6 of the 10 cities with the largest percent decreases in NDVI from 2014–2018 to 2019–2023. By contrast, 39 of the top 50 cities with the greatest percent increase in NDVI between these two time periods were in Eastern Asia. The relative magnitude of percent changes in NDVI generally mirrored changes in absolute terms. There were many outlier cities across several regions. For example, five Venezuelan cities: Barcelona, Maturin, Barquisimeto, Maracay, and Valencia had increases in NDVI across the two periods despite a general decline in urban greenspace across Latin America and the Caribbean. Buram, Sudan in Northern Africa and Gonda, India in Southern Asia were also positive greenspace outliers. In contrast, many cities were negative greenspace outliers in their regions including Auckland, New Zealand; San

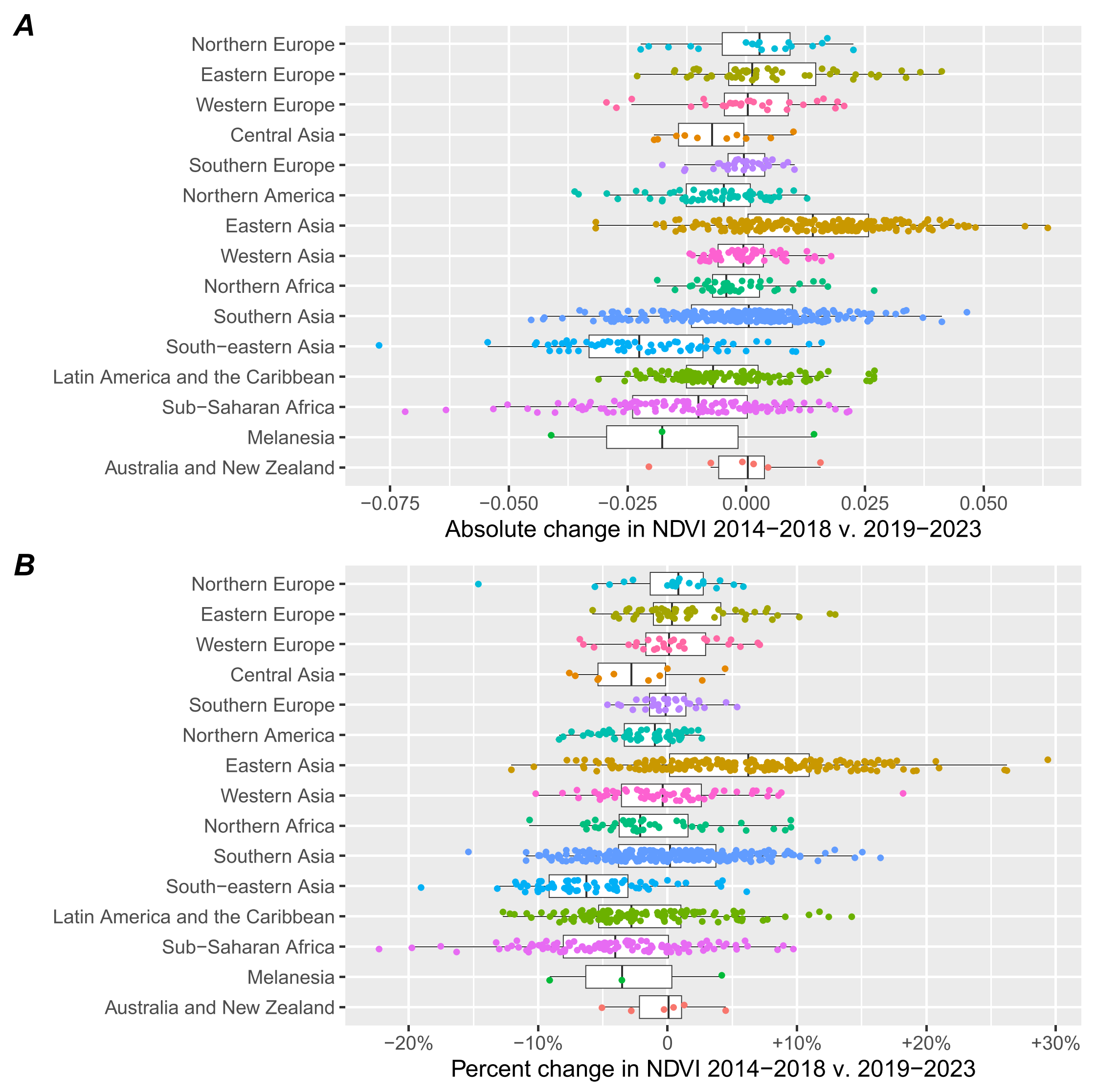

Figure 3. Change in average population-weighted greenest season normalized difference vegetation index (NDVI) from 2014–2018–2019–2023 in absolute (panel (A)) and relative (panel (B)) terms, by geographic region, for 1041 cities globally. Each dot represents a city, colored by geographic region. Regions are arranged by the average latitude of their included cities.

Antonio and Providence, United States; Mataram, Indonesia; Lakhimpur, India; Drachevo, Macedonia; and Dortmund and Wuppertal, Germany. There is likely a mix of driving factors contributing to each of these cities' greenspace changes. Some of the negative outliers such as Auckland, San Antonio, Mataram, Lakhimpur, and Drachevo have experienced urbanization over the past decade that may be contributing to their decline in greenspaces. Other cities situated near one another such as the five cities of northern Venezuela and the two German cities likely have experienced similar temperature and rainfall changes due to weather and climate change.

In general, cities classified as 'Arid' by the Köppen–Geiger climate classification did not experience large changes in NDVI between the two time periods (median change: <0.000, range: −0.046, 0.041) (figure 4(A)). The tropical climate classification became less green from 2014–2018 to 2019–2023, with a median city change of −0.010 (range: −0.077, 0.033), while continental cities generally increased in NDVI (median: 0.006, range: −.035, 0.048). Like arid cities, the median change in urban greenspace across temperate cities was close to zero (−0.001), with increases and decreases across individual cities (range: −0.045, 0.064).

The median percent change in population-weighted peak season NDVI was −0.01% in arid, −0.2% in temperate, +1.7% in continental, and −3.1% in tropical cities (figure 4(B)). Temperate cities had the largest spread in relative terms (44.8 percentage points) compared to continental (20.8), tropical (37.4) and arid (29.1) cities. NDVI decreased by about 20% in three tropical cities (Goma, Democratic Republic of the Congo; Yaounde, Cameroon; and Mataram, Indonesia) and increased by over 20%

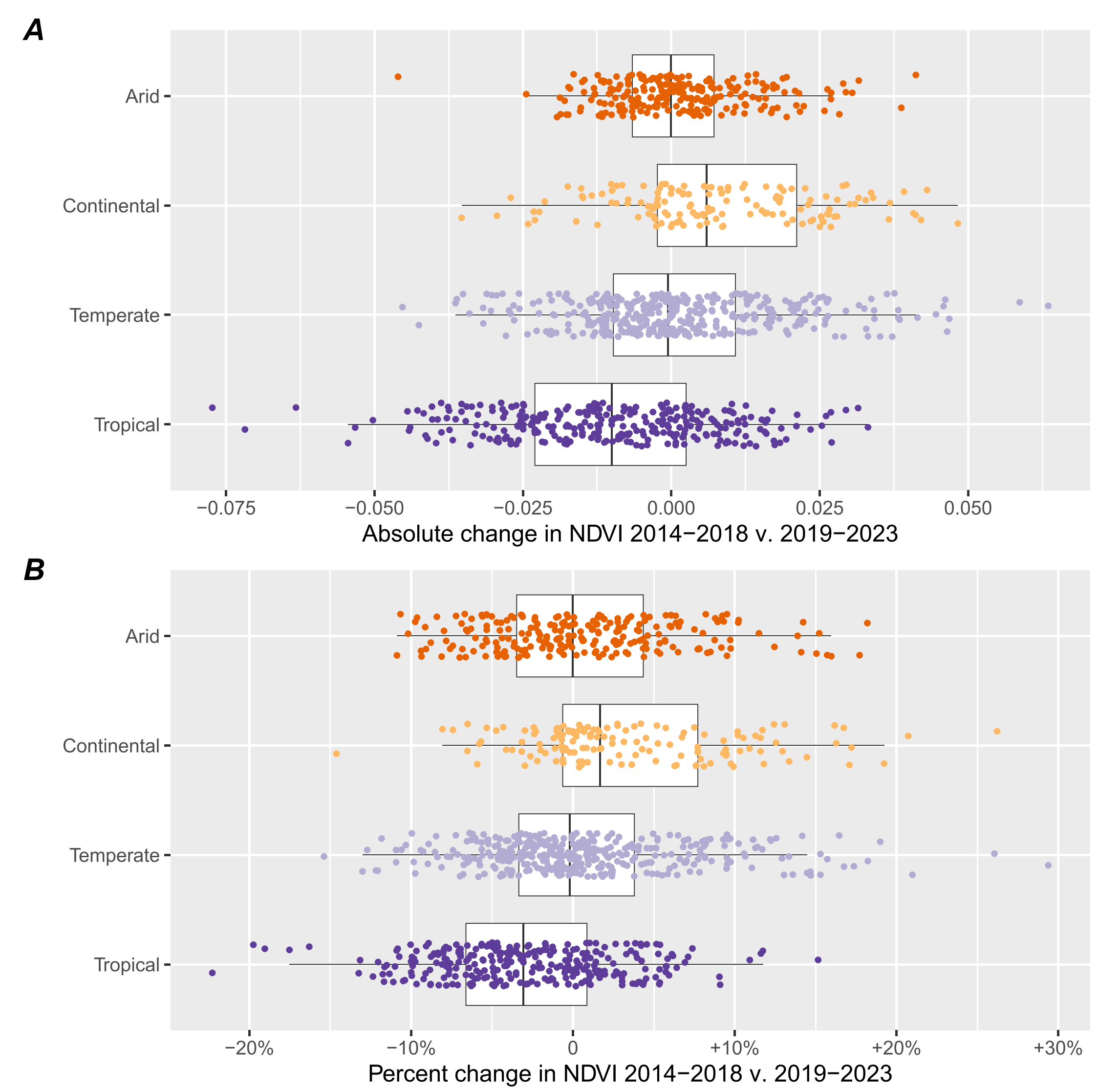

Figure 4. Change in city average population-weighted greenest season normalized difference vegetation index (NDVI) from 2014–2018 to 2019–2023 in absolute (panel (A)) and relative (panel (B)) terms, by Köppen–Geiger climate classification. Each dot represents a city, colored by climate classification. One city classified as 'Polar' was removed from the figure (El Alto, Bolivia; change in NDVI: −0.013 (−10.5%)).

in three temperate cities (Zhengzhou, Shiyan, and Zhenjiang, China) and two continental cities (Pyongyang, North Korea; and Rizhao, China).

Globally, NDVI changes from 2014–2018 to 2019–2023 were associated with an estimated mean of 0.19 (95% CI: 0.12, 0.27) more all-cause premature deaths per 100 000 annually to the 2020 population (figure 5). The premature mortality impact from urban greenspace change was not evenly distributed around the world, with fewer associated deaths in areas that experienced increases in NDVI across the time periods and more associated deaths in areas where NDVI decreased (figure 5(A) and (B)). The range in associated mortality from greenspace changes spanned fewer to more deaths, reflecting that there were cities across all regions that experienced both increases and decreases in NDVI. Changes in associated deaths closely mirrored trends in NDVI, with the largest median reductions in Eastern Asia. Due to several city outliers with large increases in urban greenspace, Eastern Europe had the largest mean reductions in deaths, with an estimated average of 7.05 (95% CI: 4.19, 9.87) avoided deaths per 100 000. Eastern Asia had a mean reduction of 4.18 (95% CI: 2.48, 5.87) annual premature deaths per 100 000 population, though even within this region there was substantial variation across cities, ranging from 21.25 fewer premature deaths per 100 000 in Shiyan, China to 13.72 more premature deaths per 100 000 in Hiroshima, Japan. Southeastern Asia and Sub-Saharan Africa had the highest increase in health burdens, with means of 3.44 (95% CI: 2.06, 4.79) and 4.58 (95% CI: 2.74, 6.40) more deaths per 100 000 respectively. Substantial intra-regional

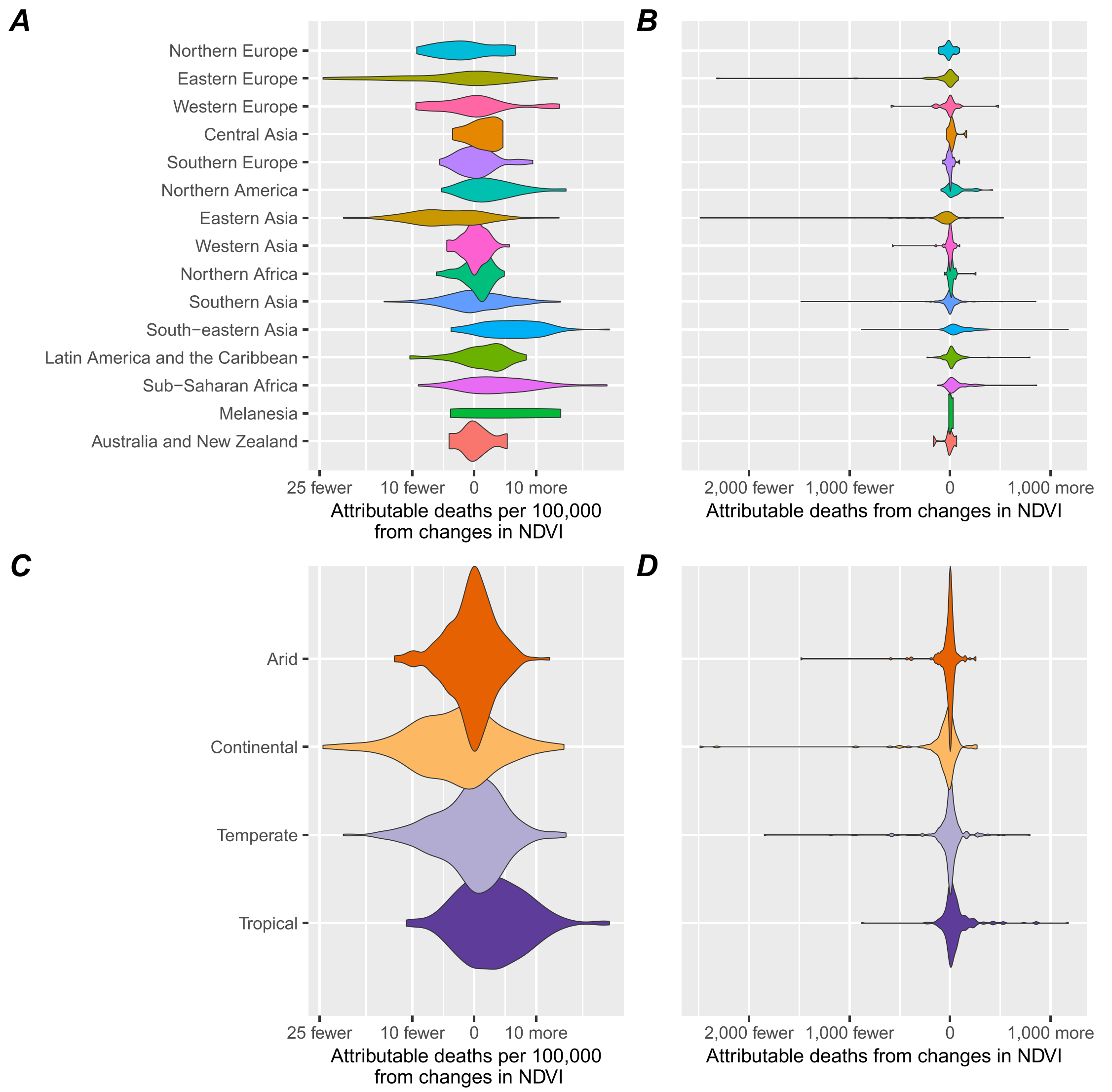

Figure 5. Changes in city-level mortality per 100 000 population (panels (A) & (C)) and in absolute terms (panels (B) & (D)) associated with changes in average population-weighted peak season normalized difference vegetation index (NDVI) from 2014–2018 to 2019–2023 to the 2020 population, by geographical region (panel (A)) and climate classification (panel (B)). Regions are arranged by the average latitude of their cities. One city classified as 'Polar' was dropped from panel (B) (El Alto, Bolivia, 4.78 more deaths per 100 000 population).

variation existed for these regions as well- ranging from 3.75 fewer deaths to 21.84 more deaths per 100 000 in South-eastern Asia and from 9.04 fewer deaths to 21.45 more deaths per 100 000 in Sub-Saharan Africa. In absolute terms, Eastern Asia had the largest health gains from changes in NDVI with an estimated 20 600 avoided deaths (95%CI: 12 200, 28 900) across all cities. Sub-Saharan Africa has the greatest absolute health burden from urban greenspace changes, with a total of 9,100 more deaths (95% CI: 5,500, 12 800).

We also considered NDVI-associated mortality changes by climate classification (figure 5(C) and (D)). Arid cities had stable NDVI values over time, and this was reflected in the average associated changes in mortality, which was very close to zero at 0.90 (95% CI: 0.53, 1.27) fewer deaths per 100 000 (range: 12.90 fewer to 12.14 more). Temperate cities were similarly fairly evenly distributed between those with fewer and more deaths associated with changes in NDVI but had a larger spread than arid cities. Temperate cities had a mean change of 0.76 (95% CI: 0.45, 1.08) fewer deaths per 100 000 (range: 21.15 fewer to 14.83 more). Tropical cities became, on average, less green over the past decade and had a mean of 2.68 (95% CI: 1.60, 3.73) more associated deaths per 100 000 (range: 10.97 fewer to 21.84 more). In contrast, continental cities became slightly greener on and had a mean of 4.31 (95% CI: 2.55, 6.03) fewer associated deaths per 100 000 (range: 24.44 fewer to 14.50 more). The spread across all climate classifications spanned reductions and additions in deaths. In absolute terms, there was an estimated 3300 fewer (95% CI: 1800, 5100) greenspace-associated deaths globally. Continental cities had the greatest reductions, with an estimated 10 900 (95% CI: 6500, 15 300) fewer deaths, while tropical cities had the greatest increases (17 300, 95% CI: 10 400, 24 200). Region- and climate classification-wide total attributable deaths per 100 000 and the corresponding 95% CIs can be found in the Supplemental data (figure S7, table S1-S2). Individual city mortality estimates are also provided (Individual city estimates).

4. Discussion

Urban greenspace varies greatly (NDVI mean: 0.270, range: 0.072, 0.580) across the 1041 cities studied and is related to region and climate classification. Overall, urban greenspace has remained stable from 2014–2018 to 2019–2023. However, individual cities experienced over 20% changes in city average NDVI in either direction. Regionally, NDVI changed over 5% in South-eastern Asia (−6.3%) and Eastern Asia (+6.2%), while cities classified as arid were the most stable. We estimated that NDVI changes from 2014–2018 to 2019–2023 were associated with an average of 0.19 (95% CI: 0.12, 0.27) additional deaths per 100 000 across the 1041 cities. While the global estimate showed almost no change, mortality changes associated with urban greenspace ranged widely, with over 100-fold higher and lower death rates across individual cities.

Our urban greenspace estimates align closely with previous work using a similar spatial scale and inclusion criteria and are considerably lower than a study using a coarser spatial resolution and more inclusive urban definition. Brochu *et al* quantified urban greenspace across the 35 most populous U.S. cities using census tracts as the unit of analysis, which are generally spatially analogous to our 100 m pixels in urban areas [19]. They reported a mean NDVI of 0.35–0.40 between 2000–2019, which aligns well with our population-weighted peak season NDVI estimates of 0.39 in 2014–2018 and 0.38 in 2019–2023 across all North American cities. Barboza *et al* estimated an average baseline NDVI of 0.52 (range: 0.11–0.72) across 978 European cities [18]. Our baseline NDVI estimates were substantially lower, with a mean estimate of 0.33 (range: 0.13, 0.46) across European cities. Barboza *et al* averaged NDVI using a 300 m buffer around each 250 m pixel, which could partially explain this discrepancy. In previous Lancet Countdown reports, NDVI was averaged to the 1 km resolution, which produced higher estimates of NDVI, with a WHO European region average of 0.37 [20]. Coarser resolution data may increase the NDVI estimate in dense urban centers, by averaging values from greener areas outside the city center. Furthermore, we limited the analysis to cities with over 500 000 inhabitants, while the Barboza *et al* study used the Organization for Economic Cooperation and Development city definition, which includes urban areas with as few as 50 000 residents. Smaller cities may be greener due to the need for less infrastructure.

Our health impact estimates differ from past work, as we compare historical changes (both negative and positive), whereas previous studies have looked at the impact of hypothetical additions in greenspace. Brochu *et al* estimated that 0.1 increases in NDVI were associated with 200, 170, and 150 fewer deaths per 100 000 across 35 American cities among those 65 and older in 2000, 2010, and 2019, respectively. We estimated that NDVI changes were associated with an average of 2.67 more deaths per 100 000 across the entire set of North American cities. Our results include the total population rather than those 65 and older and are inclusive of 57 cities including 8 Canadian cities. For these reasons, the magnitude of the results is not directly comparable. Furthermore, we found that NDVI decreased in North American cities over our study period, explaining the difference in sign of our results. Barboza *et al* estimated health impacts of increasing NDVI to the World Health Organization's recommendation of universal access to greenspace and reported large variability across European cities ranging from 1–59 fewer deaths per 100 000 inhabitants among adults 20 years and older. Our health impact estimate of the associated mortality change from NDVI changes across European cities was 0.41 fewer deaths per 100 000 (range: 24.44 fewer to 13.75 more). Though we included the total population rather than restricting to adults, European cities experienced both positive and negative changes in NDVI over the study period, resulting in health estimates that were smaller in magnitude than those found by Barboza *et al.* Our use of total population may overestimate the health benefits of increased greenspace and health losses from decreases.

There are several key limitations to our study. We use one exposure-response function globally from a large-scale meta-analysis that includes populations from the Northern America, Eastern Asia, Southern and Western Europe, and Australia and New Zealand regions, with significant representation of temperate and continental climates and limited inclusion of select arid and tropical cities, to be as generalizable as possible. However, most of the studies were conducted in Europe and North America in temperate and continental climates, where vegetation may differ from other climate zones. Fewer data points contribute to the exposure-response curve at very high or low NDVI levels, such as may be found in tropical or arid climates. The relationship between NDVI and all-cause mortality may be related to current NDVI levels and other factors that vary by region and climate. While some of the causal pathways that link NDVI to health, such as reduced stress from viewing greenspaces, are universal, others likely differ across climates. For example, increasing NDVI in arid climates may consist of adding vegetation which can survive in dry climates, which may provide less shade and relief from the heat than leafier plants requiring more water. Adding greenspace in arid climates could still provide health benefits through other pathways, such as providing natural beauty and places to exercise and gather. Additionally, spending more time outdoors may increase people's exposure to air pollution and accidents in developing cities with greater traffic and less regulations. We extrapolated the results of the meta-analysis, which largely consists of studies from developed countries in temperate and continental climates to a global set of cities. Thus, the uncertainty of our estimates is larger for cities in regions and climate zones not well-represented by the meta-analysis. These unmeasured sources of uncertainty are not captured by our error estimates. While the current evidence base linking greenspace and all-cause mortality does not support a city-specific approach, there are many city-level factors that could theoretically influence the relationship between greenspace and mortality. City walkability (safety, pedestrian infrastructure, traffic, etc), time spent near home where we have measured their exposure (employment type, leisure time, etc), and baseline environmental hazards (heat, air pollution, noise, etc) may impact the strength of the greenspace-health relationship across different cities in addition to individual factors like age, socioeconomic status, and gender. While the meta-analysis we used controls for many of these city and individual factors, the populations included might not be generalizable globally.

Roughly half of the nine studies included in the meta-analysis adjusted for air pollution and two of them controlled for some aspect of climate or temperature. Because of the heterogeneity in confounders across studies, the estimated exposure-response function captures some amount of the benefits from reduced environmental harms such as the urban heat island effect and air pollution. The results presented here likely underestimate the total health benefits from added greenspace and overestimate those provided by greenspace independent of its impact on other environmental harms. Furthermore, the timescale on which exposure to higher levels of NDVI improves health is unknown. The studies included in the meta-analysis range in follow-up time from four to 18 years. If the changes in NDVI across the two time periods do not reflect true trends but rather temporary increases or decreases, our results will not be applicable to future heath projections. Moreover, the studies included in the meta-analysis compare NDVI across locations. Our study assumes that the mortality relationships found when comparing spatial differences in NDVI can be applied to temporal differences.

We used NDVI to measure urban greenspace, which has limitations. NDVI is the most common metric used in epidemiological studies, because of its fine spatial and temporal resolution, which lends itself particularly well to longitudinal studies and urban settings. However, NDVI is a function of the greenness of vegetation, which can miss important factors influencing usability such as land ownership, perceptions of safety, and infrastructure. Finally, we used baseline mortality rates from the GBD study, which were largely available at the country level, and may not be reflective of baseline mortality rates in cities.

We found substantial inter-annual variation in NDVI, particularly in cities outside of arid climate zones. Differences in NDVI between two individual years are therefore more likely to reflect weather patterns than city-wide efforts towards urban greening. Urbanization in the past decade could also contribute to these changes, as we used a consistent urban boundary definition across the 10 year period, however cities may have grown and morphed over this time. We explored changes in urban fraction in a sensitivity analysis (figures S8 and S9) and found no correlation between the urban fraction across cities and year. To account for cyclical patterns, we compared differences between two 5 year periods. These time periods roughly align with the Lancet Countdown's reporting, which has published greenspace exposure dating back to 2015, while creating two equal time periods and using the latest available data. While our exposure definition limits the influence of weather on our NDVI estimates, the inter-annual variation highlights difficulties with using NDVI for health impact assessments. Recent efforts to increase urban greenspace may be attenuated in our study by using 5 year averages. We aim to disentangle the impact of different drivers of changes in NDVI in future work to provide a better understanding of the impact of efforts to expand urban greenspace amidst climate change, urbanization, and meteorologic fluctuations.

5. Conclusion

We found large inter-annual variability in NDVI, likely driven by a mix of weather, climate change, urban development, and efforts to increase urban greenspace. Globally, urban average NDVI remained relatively stable from 2014–2018 to 2019–2023. However, we observed NDVI changes in individual cities of over 20%. Urban NDVI changes between these two periods were associated with a mean of 0.19 (95% CI: 0.12, 0.27) deaths per 100 000 globally each year, ranging from 24.44 fewer to 21.84 more deaths per 100 000 across the 1041 cities. Future research should explore alternative measurements to NDVI and target levels of urban greenspace for healthy and sustainable cities.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi:%2010.2905/53473144-B88C-44BC-B4A3-4583ED1F547E; https://developers.google.com/earth-engine/datasets/catalog/JRC_GSW1_4_GlobalSurfaceWater; https://developers.google.com/earth-engine/datasets/catalog/LANDSAT_LC08_C02_T1; https://developers.google.com/earth-engine/datasets/catalog/JRC_GHSL_P2023A_GHS_POP; https://doi:10.6069/1D4Y-YQ37.

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